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DISSEMINATION OF THE KILOGRAM FOLLOWING ITS REDEFINITION

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Abstract:
On 20 May 2019 a new definition of the SI unit of mass, the kilogram, came into force. The kilogram is now defined based on a fixed numerical value of the Planck constant. This leads to a new situation for mass metrology that in principle every National Metrology Institute can realise the kilogram. To ensure global uniformity, the Consultative Committee for Mass and Related Quantities (CCM) recommended that during an initial phase the dissemination of the kilogram shall be internationally coordinated, by basing it on a so-called 'Consensus Value'. This paper describes the different phases of the dissemination of the kilogram, the determination of the Consensus Value and its impact on national mass scales. The paper concludes with an outlook on future developments of kilogram realisation and dissemination techniques.

Keywords: kilogram; redefinition; SI units; consensus value

1. INTRODUCTION

Since 1889, the kilogram was defined as the mass of the International Prototype of the Kilogram (IPK), kept at the Bureau International des Poids et Mesures (BIPM) in Sèvres, France. This definition was abrogated on 20 May 2019, when the kilogram was redefined, at the same time as the ampere, the kelvin and the mole. The new definition of the kilogram is based on a fixed numerical value of the Planck constant [1], [2]. This brought to an end the period during which the kilogram was defined by an artefact. In contrast to the previous situation, where access to the IPK was only possible at the BIPM, the new definition in principle allows every National Metrology Institute (NMI) to realise the kilogram. The realisation methods that are currently recognised by the *mise-en-pratique* for the kilogram are the Kibble balance [3] (and the similar joule balance) and the X-ray crystal density (XRCD) method [4]. This poses the question of how consistent realisations made by different NMIs using different experiments will be. In 2017 the numerical value of the Planck constant, which would be used in the definition of the kilogram was determined by a special adjustment of the fundamental constants by the CODATA Task Group on Fundamental Constants [3]. At that time, the data sets from Kibble balances and the XRCD experiments were not in agreement at the level of their respective uncertainties. If these experiments had been used to realise the kilogram, the differences would have been up to 70 µg. The Consultative Committee for Mass and Related Quantities (CCM) therefore recommended in 2017 an internationally coordinated dissemination of the kilogram, instead of dissemination from national, independent realisations. Dissemination should be based on the so-called 'Consensus Value' to ensure world-wide equivalence and stability of the kilogram until a sufficient level of agreement between realisation experiments could be achieved. The Consensus Value should be calculated and updated based on the results of a series of periodic comparisons of kilogram realisations.

The paper describes the different phases of the dissemination of the kilogram, the determination of the Consensus Value and its impact on national mass scales. The paper concludes with an outlook on future developments of kilogram realisation and dissemination techniques.

2. THE PHASES OF THE DISSEMINATION OF THE KILOGRAM

The CCM recommended that until the agreement of independent realisations could be considered as being satisfactory, every two years a key comparison of kilogram realisations with Kibble balances and XRCD experiments would be carried out. Following each comparison, a new Consensus Value, representing an 'international mean kilogram', would be calculated. Since the first key comparison was launched only after adoption of the new definition, a Consensus Value was not immediately available. The CCM therefore decided that the process for the transition of traceability from the IPK to independent NMI realisations of the kilogram should go through different phases [6].

The first phase started at the time of implementation of the new definition, 20 May 2019, and ended with the adoption of the first Consensus Value on 1 February 2021. During this phase, the traceability to the Planck constant was established via the IPK. This was possible, because the process towards the redefinition ensured that there would be no step change in mass values when going from the previous to the new definition. In other words, the numerical value chosen for the Planck constant was based on the definition of the kilogram with respect to the IPK. In the first phase, the mass of the IPK was therefore still 1 kg but with an uncertainty of 10 μg with respect to the Planck constant. This was the uncertainty of the adjusted value of the Planck constant in the 2017 CODATA least-squares adjustment [5]. Following the redefinition, when this value was fixed, this uncertainty was transferred to the mass of the IPK. As a consequence, in Phase 1, all mass values remained unchanged, but the NMIs with the smallest mass calibration uncertainties had to increase their CMCs (internationally recognised Calibration and Measurement Capabilities) to take into account the additional uncertainty of 10 μg in the IPK.

The second phase started with the adoption of the first consensus value on 1 February 2021 (see Section 3). This phase will continue until the CCM decides that the agreement between a sufficient number of independent realisation experiments is such that the kilogram can be disseminated from these experiments. The CCM has established a list of criteria for the transition to this third, final phase:

(a) A minimum of five consistent realisation experiments which:
    I. achieve key comparison results with a relative standard uncertainty of 40 parts in 10^9 or better;
    II. demonstrate consistency with the KCRV (key comparison reference value);
    III. demonstrate stability by producing consistent results for two consecutive key comparisons.

(b) At least three of the realisation experiments meeting the above criteria should have uncertainties less than or equal to 20 parts in 10^9.

(c) The consistent set of experiments must include two independent methods of realising the SI unit of mass.

(d) The difference between the Consensus Value for the kilogram and the KCRV for the final key comparison is less than 5 parts in 10^9.

In the final phase, NMIs with realisation experiments will need to follow the rules of the CIPM MRA (Mutual Recognition Arrangement) [7] to be able to publish their CMCs and to provide internationally recognised traceable mass calibrations, based on these CMCs. This requires in particular participation in key comparisons to demonstrate the equivalence with other NMIs' calibrations.

3. DETERMINATION OF THE CONSENSUS VALUE

The CCM decided that the Consensus Value should be determined from the results of a series of biennial key comparisons of kilogram realisations. To avoid significant step changes from one Consensus Value to the next, the value should be calculated as the arithmetic mean of the key comparison reference values (KCRV, typically the weighted mean of the participants' results) of the last three comparisons. For the first two calculations, the missing comparison results would be replaced with the results of a BIPM calibration campaign using the IPK in 2014 and a trial comparison of realisation experiments (Pilot Study) in 2016.

Since the reproducibility of most realisation experiments still needs to be demonstrated, a stable mass reference is needed in-between the comparisons, to meaningfully compare their results. This is provided by the 'as-maintained' BIPM mass unit, which is maintained using the set of twelve BIPM Pt-Ir 1 kg working standards. These were calibrated in 2014 against the IPK. The BIPM has adopted a hierarchy with three different levels of usage to reduce the risk of undetected mass changes. The BIPM working standards are involved in each of the key comparisons and since the 'as maintained' BIPM mass unit is significantly more stable than the realisation experiments, this allows the evaluation of KCRVs of the different comparisons against a stable reference and to calculate a meaningful arithmetic mean.

The first key comparison, CCM.M-K8.2019, was launched in 2019, shortly after the adoption of the new definition. The BIPM was the pilot laboratory of this comparison of four Kibble balances (BIPM, KRISS, NIST, NRC), one joule balance (NIM) and two applications of the XRCD method (NMIJ, PTB). Each of the participating NMIs determined the mass under vacuum of one or two 1 kg mass standards using their realisation experiment. The mass standards were then sent to the BIPM, where they were all compared with BIPM reference standards under vacuum. The results of these weighings, together with the measurement results of the NMIs, allowed the determination of the differences between mass values attributed by the participants to a nominal 1 kg mass standard. The key comparison reference value was calculated as the weighted mean of the participants' results. It has a deviation of -0.019 mg with respect to the mass unit maintained by the BIPM working standards, with a standard uncertainty of 0.008 mg. The results of this comparison are shown in Figure 1 [8]. The chi-squared test for consistency of the data set was passed, although the two results with the smallest uncertainties were not in agreement with each other.

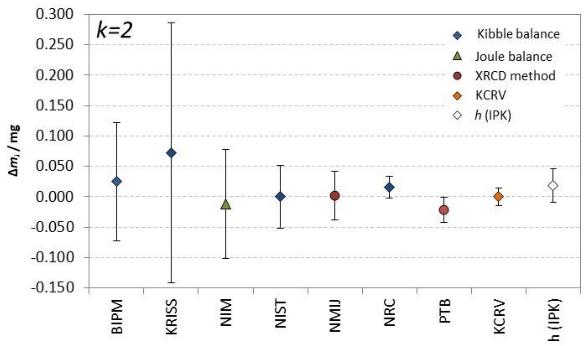

Figure 1: Differences Δm_i between mass values attributed to 1 kg mass standards using the realisation experiments of the participants and the KCRV, calculated as the weighted mean. The difference between the realisation based on the BIPM working standards, traceable to the Planck constant through the IPK, and the reference value is also indicated, on the right.

Following the completion of the first key comparison, the first Consensus Value was determined. It can be presented as the mass value attributed to the IPK (which was historically always exactly 1 kg) based on an average of the absolute kilogram realisations. Following the decision of the CCM [6], the Consensus Value was calculated as the arithmetic mean of the following three results:

- the last use of the IPK during a calibration campaign in 2014. At that time the mass of the IPK was – by definition – 1 kg.
- the reference value of the CCM pilot comparison of realisation experiments in 2016. Based on this reference value, the mass of the IPK would be 1 kg + 0.012 mg.
- the key comparison reference value of CCM.M-K8.2019. Using this reference, the mass of the IPK would be 1 kg – 0.019 mg.

The arithmetic mean of these three results is 1 kg – 0.002 mg for the mass of the IPK. The CCM had decided that the standard uncertainty of the Consensus Value should be set at 0.020 mg [6]. This value is not calculated from the data but based on the typical uncertainty of "mature" realisation experiments, the target uncertainty of newer realisation experiments which are predicted for the next 10 years and for setting the expectations on future uncertainties from individual experiments.

The Consensus Value was officially adopted by the CCM on 1 February 2021 [9]. The consequence is that the masses of all national mass standards, previously traceable to the IPK, are nominally reduced by 0.002 mg. Since this change is small in relation to the uncertainty of the Consensus Value and the CMCs of the NMIs, no adjustment to the international mass scale needed to be made. It was indeed one of the objectives of this process to ensure that it would not introduce any significant step changes. However, adjustments to the CMCs of a number of NMIs were necessary to take into account the uncertainty of the consensus value. At the BIPM, the uncertainty of the calibration of a 1 kg Pt-Ir prototype is now 0.021 mg, dominated by the uncertainty of the Consensus Value.

The second key comparison of kilogram realisations, CCM.M-K8.2021, was launched in late 2021. It has nine participants, six using a Kibble balance (BIPM, LNE, METAS, NIST, NRC, UME), one using a joule balance (NIM) and two applying the XRCD method (NMIJ, PTB). The comparison scheme is identical to that of the first key comparison, in that each participant determines the mass in vacuum of one or two travelling standards and then sends them to the BIPM for comparison. The final report is expected in September 2022. The key comparison reference value of this comparison will then be used to re-calculate the Consensus Value.

4. THE WAY FORWARD

4.1. A Move to Sovereign Realisations

The Consensus Value for the kilogram, as described in Section 3, is being used as a way to disseminate a consistent value for the kilogram. This approach is currently necessary due to the discrepancy between realisation experiments, as illustrated by the results of the first key comparison of realisation experiments (CCM.M-K8.2019) shown in Figure 1. Such a key comparison will take place every two years and it is envisaged that the reproducibility, uncertainty and agreement of the realisation experiments will improve and that the CCM criteria for transition to the use of individual realisation experiments, outlined in Section 2, will be met. Once these criteria are achieved, experiments which have demonstrated reliable equivalence with the KCRV will be able to realise the SI unit of mass independently. With time the number of experiments will increase and the dissemination of the SI unit of mass will become more distributed.

4.2. Simplification of Experiments

The current group of realisation experiments (essentially those that participated in the pilot study and key comparison) were initially designed to determine the Planck (or Avogadro) constant. This focus means that the experiments were designed to give the best uncertainty possible with little consideration for ease of use. Figure 2 shows as an example the BIPM Kibble balance apparatus which is about two metres tall.

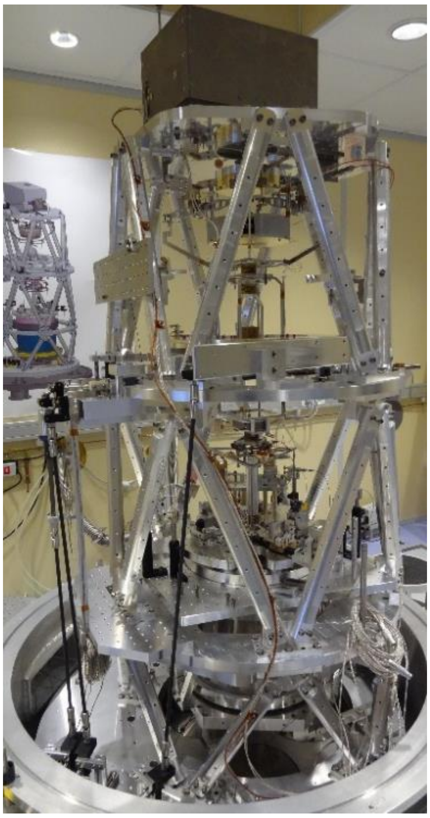

Figure 2: The BIPM Kibble balance apparatus

NMIs are now working on simplifying the mechanical design of the Kibble balance apparatus to make it more appropriate for the regular "routine" realisation of the kilogram. NPL, working with NMISA and RISE, are producing a next-generation Kibble balance [10] based on a seismometer type mechanical system (Figure 3). The overall height of the balance is about 1.5 m and the design and operating principles make the balance much less sensitive to issues with coil/magnet alignment and therefore closer to a "turn-key" solution to realising the kilogram at NMI level.

As well as the complicated mechanical design of current Kibble balances, a further limitation to wider adoption of the Kibble balance is the need for external measurement standards for voltage, resistance and gravimetry. At present these are costly and complicated additions to the measurement apparatus, being cryogenic Josephson Voltage Standard and Quantum Hall Resistance devices and high accuracy gravimeter are delicate and require a skilled user. These standards are generally available at most NMI but not more widely.

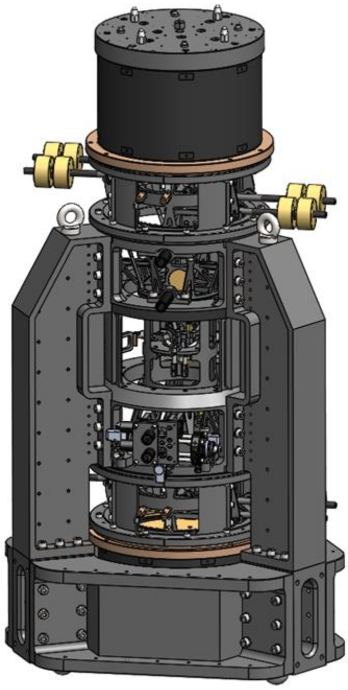

Figure 3: NPL next-generation Kibble balance design featuring seismometer based mechanical system

4.3. SI at the Point of Use

In order to fully embrace the redefinition of the kilogram, a means of establishing SI traceability for measurements of mass (and related quantities) at the point of use should be the ultimate aim. In the short term, measurements of micro-mass and low force are areas which can reasonably employ existing Kibble balance technology, including electrostatic balances [11], to improve on the current state of the art. Traceability for mass standards of 1 mg and below is important for a number of industrial areas such as pharmaceutical research and production [12]. The current traceability chain, back to a kilogram standard, results in uncertainties of the order of 0.1 %, which can significantly affect research conclusions and drug efficacity. A micro-Kibble balance [11] such as the concept design shown in Figure 4 could significantly reduce this uncertainty and improve the reliability of measurements made at this level.

Figure 4: Design for micro-Kibble balance

The development of "commercial" Kibble balances to work at the level of a few grams up to 1 kg [10], [13] in part relies on having a room temperature voltage reference with the accuracy and stability at an uncertainty better than 1 in 10^7 which is currently close to the state of the art. Work is underway at a number of NMIs to simplify the construction of Kibble balances and supporting apparatus to demonstrate that such end-user devices are feasible. Figure 5 shows NPL's simplified Kibble balance designed for end-user applications.

Figure 5: NPL end-user Kibble balance demonstrator

In addition to generating a defined force (and thus mass) Kibble technology can also be adapted to the generation of accurate torques. The generation of reliable torsional forces is currently difficult not only because it needs to combine measurements of mass and length but also because the repeatability of torques produced is reliant on the sound mechanical design and integrity of the apparatus, which is difficult to determine. Using an adapted Kibble balance to generate torque has the potential to improve both the accuracy and reliability of torque generation and measurement. The development of apparatus such as the Electronic NIST Torque Realizer (ENTR) [14] shown in Figure 6 or the new torque standard machine of NMIJ-AIST [15], [16] is already underway.

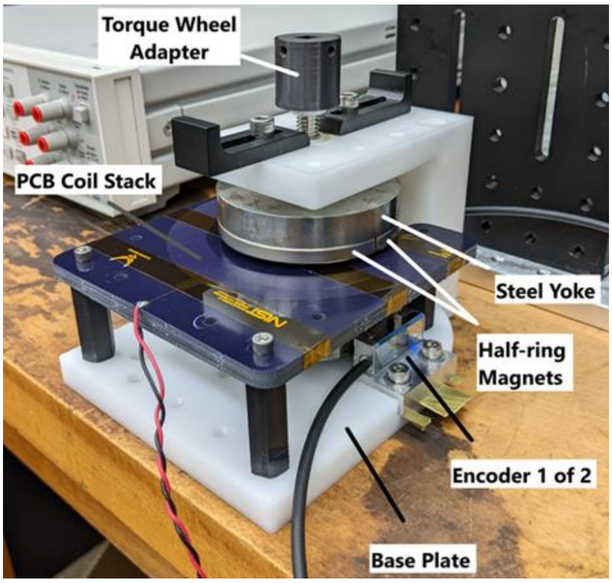

Figure 6: Electronic NIST Torque Realizer (ENTR)

5. SUMMARY

On 20 May 2019 a new definition of the kilogram came into force. The new definition allows for the first time the independent realisation of the mass unit in different NMIs. At present, the level of agreement between different sovereign realisations does not provide a sufficient global uniformity of dissemination. Therefore the dissemination of the mass unit from NMIs and the BIPM will be internationally coordinated until sufficient agreement between different realisations has been reached. This coordination is based on the so-called Consensus Value - a sort of international mean kilogram - which is derived from a series of periodic key comparison of realisation experiments. The first Consensus Value was adopted on 1 February 2021 and introduced a negligible change of mass values compared with the previous traceability to the IPK. In late 2021 a new key comparison was started, the results of which will contribute to the determination of a new Consensus Value. In future the Kibble balance and XRCD experiments will be used to realise the mass scale at a national level and further ahead the technology will be available for end-users to make measurements with direct traceability to the SI unit of mass at the point of need.

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